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INTERACTIVE DIGITAL CORRELATION TECHNIQUES
FOR AUTOMATIC COMPILATION OF ELEVATION DATA

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ABSTRACT

A program using digital correlation techniques has been
implemented on the Digital Image Analysis Laboratory (DIAL)
to automatically extract elevation type data from stereo-
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operator to view on a display unit the stereoscopic model
and the computed match-point coordinates in 3-D using ana-
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INTRODUCTION

Over the past ten-plus years the Computer Sciences Labora-
tory (CSL) of the Engineer Topographic Laboratories (ETL)
has sponsored in-house and private industry efforts to
develop digital techniques that can be applied to extract
elevation data automatically from a stereoscopic pair of
photographs. One of the first efforts was performed for
ETL by Keuffel and Esser Company (K&E) (Rosenberg, 1971,74)
and was aimed towards the development and testing of an
algorithm for digital correlation using the "infiltration
method" - a complex process that follows the path of
easiest correlation rather than a defined path in local
space. Much of the philosophy developed by the K&E effort
was used later in a comprehensive, five-phase study by
Control Data Corporation (CDC) (Panton, 1978) aimed at
algorithms development, implementation of the algorithms
on special purpose, high-speed "Flexible Processors,"
actual testing on stereoscopic imagery and development of
preliminary specifications for a digital stereoscopic image
processing system.

Prior to and overlapping the CDC effort, in-depth studies
were performed in-house (Crombie, 1974,75,76) to isolate
the cause-effect relationships between digital correlation
results and changes to the various combinations of parame-
ters that can be used in a digital stereoscopic image
matching process. All of the studies involved software
that was run in a batch mode and, consequently, the results
had to be evaluated using laborious, time-consuming statis-
tical analyses of large amounts of data.

In order to more readily examine, evaluate and edit the

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data from the in-house studies, software was generated for the Digital Image Analysis Laboratory (DIAL) which was being developed at ETL in the general time frame that the CDC and in-house studies were conducted. With the advent of the DIAL, which is to be described later, a means was available for image display and manipulation along with the opportunity to interact with the software controlling the computational process. This modest effort aimed at the visual examination of batch mode results soon evolved into a complete DIAL compilation program which, hereafter, will be referred to as the Digital Interactive Mapping Program (DIMP).

The DIMP was generated to serve the following purposes:
. Minimize the time required to perform digital correlation tests and to evaluate results.
. Perform studies for algorithm development.
. Test means for visual display of results and for data editing.
. Demonstrate an automatic, but interactive, means for the compilation of elevation data using digital image processing techniques.

In the implementation of the DIMP, several of the features suggested by the CDC studies were incorporated; especially in regard to the stereoscopic presentation of the digital images, stereoscopic presentation of the correlation results and data editing techniques. On the other hand, the results obtained in the in-house efforts were relied on heavily for the implementation of an algorithm and in the selection of options and parameters, such as window sizes, point spacing, quality checks, etc. The DIMP is described in the following sections in terms of the equipment used, the algorithm, operating procedures and examples of results obtained with the program.

THE DIAL

The Digital Image Analysis Laboratory (DIAL) is a large-scale, interactive system designed for research and development activities in digital image processing. It is part of the ETL computer facility which consists primarily of a host computer subsystem, a STARAN subsystem and an interactive subsystem. The Control Data Corporation CDC-6400 computer is used in a time-sharing mode with other ETL users as the host computer for the DIAL system and thereby performs practically all of the processing and control functions. The Goodyear Aerospace STARAN computer is an associative array processor that is used, because of its high-speed and parallel-processing capabilities, to perform computationally bound tasks. It is not used with the DIMP program and, therefore, will not be discussed further. The interactive subsystem of the DIAL is that part which makes the DIMP possible since it permits the operator to display and view the digital photographic images and the correlation results and, when deemed necessary, to interrupt the processor to change program parameters and variables.

The interactive subsystem consists mainly of two work

stations, one of which is shown in Figure 1. Both are con-

Figure 1. DIAL Work Station.

trolled by a DEC PDP 11/50 computer that is interfaced to
the CDC 6400. The host computer does practically all of
the processing but some simple local operations can be done
concurrently on the PDP 11/50. Each of the two work sta-
tions consists of two COMTAL 8300 display monitors, a
TEKTRONIX alphanumeric terminal, a XY-tablet and one track-
ball unit per monitor. One TEKTRONIX hardcopy device is
used to copy information from both terminals.

Each display unit features refresh storage of three digital
image memories characterized by an array of 512 x 512
elements (or pixels) whose grey shades can vary in magni-
tude from 0 to 255 (8-bits). Each monitor also has three
1-bit, 512-x 512-pixel overlay memories and one 1-bit,
512-x 512-pixel fast graphics memory. The graphic over-
lays are used to superimpose graphic images over the 8-bit
images in color; and the fast graphics plane is used to plot
graphic symbols such as dots, lines, circles, etc. The
monitors can be operated in a black and white or true-color
mode at the discretion of the operator. In the DIMP the
true-color mode is used to display the left image of a
stereoscopic pair in both blue and green to give cyan. The
right image is displayed in red. By using the anaglyphic
glasses, the operator can view the superimposed red and
cyan images in three-dimensions (3-D). A 3-D profile can
be viewed by plotting one line in cyan and the other in red
on the graphic overlays and, likewise, a "floating" dot can
be obtained by using a red cursor and an equivalent size
dot plotted in cyan on the fast graphics plane. The pro-
file and dot applications are described later in more
detail.

THE IMAGES

Practically all experiments run with the DIMP involved a
stereoscopic pair of images called RECO1 and RECO2. These
are 2-x 2-inch subsets taken from 9-x 9-inch photographs
of the Phoenix, Arizona area. The photographs were aligned

and digitized on a microdensitometer comparator with the direction of flight parallel to the scanning axis of the comparator. There is, therefore, practically no skew between images and no Y-parallax since the original photographs are at the same scale and essentially vertical. The images were digitized at a pixel and line spacing of 24 μm (micrometer) using a spot size of 34.5 μm. A total of 2048 lines were recorded with a 10-bit representation of each grey-shade value. The digitized data were recorded on tape and, as required by the DIAL, transferred to a disk pack.

The original photographs were taken from an altitude of approximately 23,500 feet with a 6-inch focal length camera. The scales are therefore about 1:47,000 and each pixel covers about 3.8 feet on the ground. When displayed on the 10-inch screen of the monitor, the viewing scale of the digitized imagery is approximately five times larger than the original or 1:9400. When a subset of 512 x 512 is taken from the 2048 x 2048 image it is displayed at a viewing scale of 1:2350.

THE ALGORITHM

General.
Given the interior and exterior orientation data and the calibration data for a stereoscopic pair of photographs, it is necessary only to obtain the corresponding X and Y photocoordinates of an image on the stereoscopic pair in order to compute its' ground position. The digital correlation algorithm described herein is used to obtain the necessary corresponding photocoordinates.

In this scheme a window of grey-shade values centered around the point in question on the left photograph is compared at every possible position within a specified search area to the grey shades on the right photograph. The position within the search area where the maximum correlation occurs will define, to a pixel precision, the location on the right photograph of the corresponding image. A curve is fitted in both the X and Y directions to the maximum correlation value and ones on either side and then analyzed to determine to a fraction of a pixel where the peak occurs. The specified pixel coordinates of the image on the left photograph and the computed pixel position on the right photograph can be transformed off-line to actual photocoordinates and subsequently used to compute X-, Y- and Z-ground coordinates.

Some of the individual considerations that must be made to implement the continuous and automatic compilation of match (or corresponding) points are discussed in the following sections.

Window and Search Area Sizes
As a matter of definition, the term "window" refers to that rectangular array of grey shades on the left photograph that is symmetrical relative to the pixel position for which a match point is required. The "search" area is a rectangular array of grey shades on the right photograph symmetrically centered about that pixel position where the

match point is estimated to occur. The estimated point in the search area is refined by the correlation process to give a computed match point.

The window size used in the DIMP is generally 15 by 15 pixels although the operator has the option of selecting any practical size and shape of window. The search area is generally two lines and six pixels (17 by 21) larger than the window but any size can be used. These sizes are large enough to give good results yet small enough to allow reasonable computational speed. They are initially select- ed by the operator but they may be altered under program control when the program logic detects conditions which call for larger or smaller array sizes.

As illustrated in Figure 2, a 15 x 15 window passed over a 17 x 21 search area results in three rows of correlation values in the Y-parallax direction and seven columns of values in the X-parallax direction. This allows for plus or minus one pixel of Y parallax removal and plus or minus three pixels correction to the estimated X position of the match point.
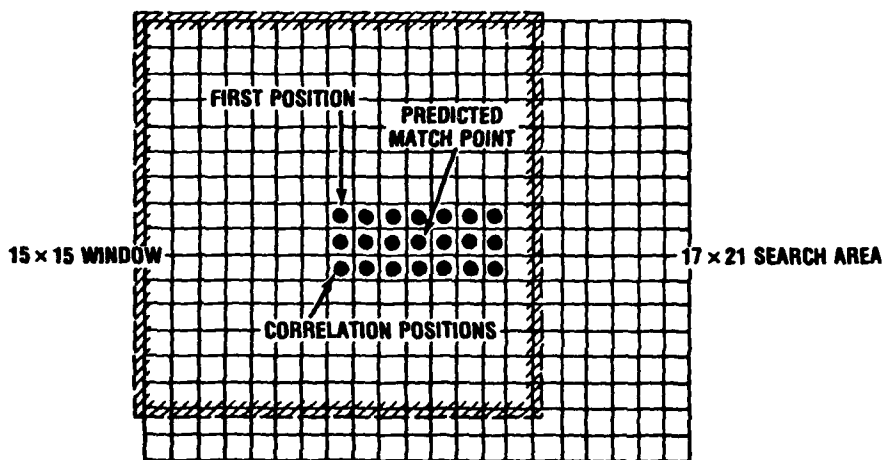

Figure 2. Relationship Between the Window and Search Area.

Point Spacing.
The compilation process proceeds from left to right and from top to bottom at equal, operator-selected increments (NCRE) on the left photograph. The spacing on the right photograph will be varied because of image displacement due primarily to relief displacements. Since match points are determined in a regular array in image space, a post- processing scheme must be used to transform any subsequent elevation data into an even array in ground space.

Any point spacing, NCRE, can be used in the DIMP but, as described in the following section, options such as window shaping depend on the point spacing. If the point spacing is too large in comparison with the window size, window shaping cannot be performed accurately. A five-or seven- pixel spacing has been used most frequently in the DIMP because they are consistent with other available options and provide acceptable speeds of operation.

Window Shaping

Since Stereophotos are taken from different perspectives,
a length of sloping terrain imaged on the left photograph
will be different in size and shape than its image on the
right photograph. In order to make the two images more
alike, one or the other must be reshaped. Since match-
point computations are performed in image space, only one
image needs to be shaped relative to the other. Ground
space computations would require that both images be shaped,
resulting in unnecessary computation time.

The smaller window of the left photo is shaped to match the
search area on the right photograph using the inverse
equations (1):

$$Y = YT \qquad\qquad\qquad (1)$$
$$X = (XT - B*YT)/A$$
$$\text{where } XT, YT \;---\; \text{New pixel coordinates}$$
$$\qquad\quad X, Y \;\;\;---\; \text{Original pixel coordinates}$$
$$\qquad\quad A, B \;\;\;---\; \text{Transformation parameters}$$

The transformation parameters A and B are computed on the
basis of previous match-point results. In the general case,
the previous four columns to the left of the "next" point
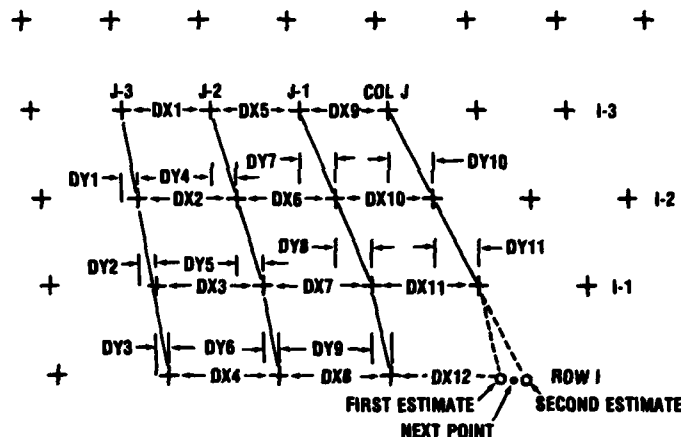and the previous four rows are used in the computation.

Figure 3. Geometric Basis for Window
Shaping and Prediction of "Next" Point.

Referring to Figure 3, the DX values represent the dis-
tances between match points on the right photograph in the
direction of X parallax. A weighted average of the DX
values are used to compute the scale, A, relative to the
incremental point spacing, NCRE, on the left photograph:

$$DX12 = (DX1*1+DX2*2+----DX10*10+DX11*11)/66$$
$$A = DX12/NCRE \qquad\qquad\qquad (2A)$$

Likewise, the skew between images, B, is computed as
follows:

$$DY12 = (DY1*1+DY2*2+---DY10*10+DY11*11)/66$$
$$B = DY12/NCRE \qquad\qquad\qquad (2B)$$

The weighted computations are used to give the previous, closer match-point results more weight but yet include further points in order to minimize the effect of errors in the immediate vicinity of the "next" point. The A and B computations are based on only four columns and four rows of previous results in order to minimize computer storage requirements. Modified versions of equations (2A) and (2B) are used when less than four rows and four columns have been compiled but the approach is generally the same.

Match-Point Prediction.

The success of the DIMP depends largely on how accurately the match-point location on the right photograph can be predicted. The correlation process is, after all, a local refinement to an estimated location and not a global search operation. The Y coordinate of the first point in each row (I,1) is determined simply by incrementing the Y coordinate of the match point above (I-1,1) by the point spacing, NCRE. This assumes the two digital images are at the same scale. The Y coordinate of each point after the first is considered to be the same as that of the previous point (I,J-1).

The X coordinate of the "next" point is determined using the weighted distance, DX12, as described in the previous section. As shown in Figure 3, the DX12 value is added to the X value of the previous point in the same row (I,J-1) to give one estimate for the next point. A second estimate for the next point is obtained by projecting a straight line through the three previous points (I-3,J;I-2,J;I-1,J) in the same column of match points. The two estimates are averaged and the result is used for the X coordinate of the next point (I,J).

At the beginning of the correlation process modifications to the above techniques are used to compute the location of the next point until four rows and four columns of match points have been determined. For the first row of points, and the first point of each row, the process uses the X and Y coordinates determined by the operator in the "starting profiles" procedure described in a later section. For rows 2 and 3, the X values are computed using only the first estimate for the point based on the DX values available thus far.

Correlation Coefficients.

The operator has the option of using the linear correlation coefficient (RXY), the covariance correlation coefficient (SXY) or the absolute difference coefficient (DXY) to determine the degree of correlation between the window and the search area. The three coefficients are computed as follows:

$$ RSY = \frac{\sigma xy}{\sigma x \sigma y} = \frac{\Sigma (X-\overline{X})(Y-\overline{Y})}{\sqrt{\Sigma (X-\overline{X})^2} \cdot \sqrt{\Sigma (Y-\overline{Y})^2}} $$

$$ SXY = \sigma xy = \frac{1}{N} \Sigma (X-\overline{X})(Y-\overline{Y}) $$

$$DXY = \frac{1}{N} \sum \left| (X-\overline{X}) - (Y-\overline{Y}) \right|$$

where X,Y .....the grey-shade values for the window and
search area.

$\overline{X},\overline{Y}$.....the average X and Y.

N.....number of elements in the window.

Because the RXY value is more consistent and predictable,
it was used almost exclusively in the DIMP in spite of the
fact that it is slower and more costly to compute.

Quality Tests.
The quality of correlation is judged good or bad based on
the magnitude of the computed correlation coefficient and
also on the magnitude of correction the correlation process
makes to the predicted location of the match point. The
terms "good" and "bad" are used here to indicate conform-
ance to statistical tests and not as an absolute measure of
quality. When the correlation process succeeds in passing
the quality test, a value of zero is assigned to the qual-
ity of that point. If it is not successful, a value of 1
is added to the quality value of the previous point in the
same column of match points. If, for example, the correla-
tion process has failed five times along a vertical column
of match points, the quality of the fifth point is 5. The
operator can set a limit on how many successive times the
correlation process can fail. When the limit is reached,
the automatic process halts and signals the operator to
intervene, if necessary, in order to get the process back
on track. The operator can also intervene at will in order
to circumvent the accumulation of bad points in obviously
poor correlation areas. Just how the operator gets the
correlation process back on track is described later in the
section on operating procedures.

Iterative Techniques.
The operator can specify the maximum number of iterations
that will be allowed in order to obtain acceptable correla-
tion results on each point. The logic used in the itera-
tive technique is given in Figure 4. The extra iterations
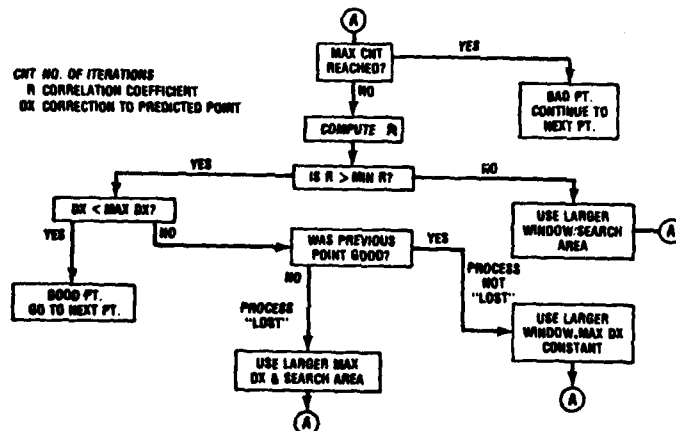

Figure 4. Iterative Software Logic.

are allowed when successful correlation is not obtained on
the first try. Depending on the quality of the previous
point, the logic allows the window and/or search areas to
increase or decrease in size. The maximum allowable cor-
rections to the computed match-point position may also be
increased. The multiple iteration logic changes the corre-
lation philosophy from one of refinement to a predicted
position to that of a limited search over a small area.

Match-Point Adjustment.
After the DIMP completes the correlation process of all
points in a given row, the quality of each point in the row
is checked to determine if any were judged to be bad. If
bad points are encountered, a straight line interpolation
is done between the good points on either side of the bad
ones to compute an adjusted match point coordinate for the
bad points. This procedure is illustrated in Figure 5.
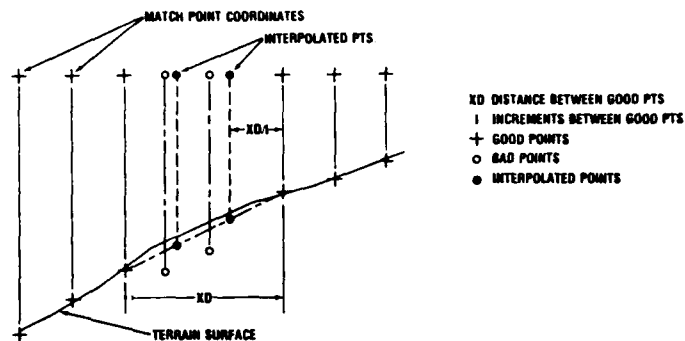

Figure 5. Match-Point Adjustment Scheme.

The interpolation scheme takes advantage of the fact that,
for the most part, the terrain is continuous and uniform
over short distances. The interpolated values are consid-
ered to be better than the "bad" points; but, for the pur-
pose of the iterative logic described in the previous sec-
tion, the points still are judged to be bad.

OPERATING PROCEDURES

Image Display.

The initial step in the operation of the DIMP is to enter
through the keyboard of the TEKTRONIX alphanumeric terminal
the names of the two photographs that constitute the
stereoscopic pair. The computer reads the digital data
from a disk pack and makes the images available for display
on one of the display units. As is the case of RECO1 and
RECO2, images larger than 512 x 512 pixels are reduced in
scale so that the full image will fit on the screen. Sub-
sets are selected from the reduced images and displayed on
the second monitor at full resolution. Using the color
capability of the monitor, the left subimage is displayed
in cyan and the right subset in red. The operator then
uses anaglyphic glasses to view the subset imagery as a 3-D
stereoscopic model.

Floating Dot.

The cursor and fast graphic capabilities of the monitors
make it possible to superimpose a "floating dot" in the 3-D
model. The floating dot is constructed in the DIMP by de-
fining the cursor as a 3 x 3-pixel array whose color is
red. In conjunction with the cursor, a 3 x 3-pixel array
is plotted in cyan on the fast graphics plane of the moni-
tor. The trackball associated with one monitor is used to
move the cursor and the fast graphics dot equally through-
out the stereoscopic model. The second trackball is used
to move the fast graphics dot in the X- and Y-parallax
directions relative to the red cursor. With the anaglyphic
glasses on, the operator sees a white floating dot which can
be moved throughout the model area and, by adjusting the
parallax between the red and cyan dots, can be "raised" or
"lowered" in elevation to appear to rest on the 3-D surface.

Parameter Selection.

Once the full-resolution subset of imagery to be compiled
has been selected and displayed, the operator is prompted
by the computer to enter the values for the parameters dis-
cussed in the previous sections on "The Algorithm." During
execution of the program, the operator can stop the program
and change these parameters to better suit the terrain con-
ditions but normally this is not necessary.

Starting Profiles.

The operator has the option of compiling as much or as
little of the 512-x 512-pixel area as desired. Large
areas would normally be selected but in special cases, such
as recompilation of bad areas or the study of select terrain
features, small areas are desired. In any case the opera-
tor selects the beginning point at the top left corner of
the desired area by placing the floating dot precisely on
the 3-D surface at that point and recording its' coordinates
on the left and right images by pushing a button on the
trackball unit. The operator then proceeds, from left to
right, to plot a profile of the major breaks in the terrain
surface. The procedure is repeated from top to bottom
starting at the previously defined beginning point on the
left edge of the compilation area. The DIMP then interpo-
lates between the gross profile points to compute "given"
estimated match-point coordinates at every increment along
the profile that corresponds to the previously selected
point spacing between correlation points. The interpolated
match-point coordinates are used as the "predicted match
points" described previously and also are used for window
spacing of the first row in the correlation process.

Automatic Compilation.

The correlation process is automatic until the operator
intervenes or the program stops due to loss of correlation.
Starting at the first row, the correlation process proceeds
left to right across the area designated by the operator
when the starting profiles were drawn. At the conclusion
of each match-point determination, the floating dot is
positioned at that match point until the next match point
is determined. The operator therefore observes the dots
moving from left to right and "up" and "down" as it follows
the shape of the terrain surface.

At the completion of each row of correlation points, lines are drawn columnwise between the last two completed rows of match points. On the left image the lines are vertical and evenly spaced since the points are predesignated when the operator selects the incremental spacing between correlation points. These lines are drawn in cyan using the fast graphics plane of the COMTAL display and are superimposed over the cyan terrain image. Red lines are drawn columnwise on a graphic overlay between the last two completed rows of computed match points and are superimposed over the red terrain image. These lines are not straight nor evenly spaced because the match-point coordinates reflect the X parallax between images due mainly to changes in elevation. Since the cyan and red lines pass through corresponding images, the operator perceives 3-D profile lines that follow the terrain surface. If the correlation results are in error, the lines will appear to "float" above or below the terrain model surface. The operator uses this visual display of the correlation results to determine if and when manual intervention is needed in order to prevent the propagation of errors in the compilation process.

The lines are plotted at the completion of each row of correlations and, therefore, the lengths of the lines grow progressively with time. This type of display permits the operator to study casually the previous results obtained in the stereoscopic model and also to anticipate well ahead just what problems may be encountered due to upcoming changes in the terrain surface. If no operator intervention is necessary, the automatic mode continues until the area selected by the operator is completed. Before proceeding to compile a new subimage, the operator will normally study the visual results on the display and decide whether or not there are any areas of the stereoscopic model that were not compiled satisfactorily. In the presence of bad results, the operator can correct the data before continuing with new areas or elect to correct the data at a later date and possibly off-line from the DIMP.

EXAMPLE OF RESULTS

One of the more desirable aspects of the DIMP is that the correlation results are displayed visually and therefore afford the operator the opportunity to rapidly judge the quality without dependence on laborious statistical analyses. The operator views the results with anaglyphic glasses but, for documentation purposes, the cyan and red lines and images can be displayed in black and white, photographed, and made into stereograms suitable for publication purposes. One such stereogram is shown in Figure 6 to illustrate the manner in which match point results are displayed.

The results shown in Figure 6 were compiled using a 15 x 15 window, a 17 x 21 search area, a two-pixel correction to the predicted match point and eight consecutive losses before the automatic process would stop. Also, four iterations per point were allowed, window shaping was performed and the linear correlation coefficient (RXY) was used. Match points were computed at increments of every seven

Figure 6.   Stereogram of Compilation "Standard".

pixels and every seventh line, but the profiles are drawn at
every third correlation point and are therefore separated
by twenty-one pixels. This keeps the profile lines from
interfering with the 3-D perception of the terrain surface.
The only available option not used in this compilation was
that of match-point adjustment of bad points by interpola-
tion between the good points.

The match-point adjustment option was not used, for the
sake of consistency, because the results shown in Figure 6
were used as a "standard" against which the results of
other tests were compared. The "other" tests were made to
show how errors can occur when, for example, the window
shaping option is not used. Match-point adjustment could
not be used in the other tests because this option is so
successful that it tends to make bad results look good and
therefore leads to erroneous conclusions.

A pocket stereoscope can be used to view the stereogram and
to judge how well the profiles conform to the terrain sur-
face. Altogether, 3265 match points were computed and only
28 points were judged to be bad--a success rate of 99.1
percent. Of the 3265 points, 3180 points (97.4 percent)
were correlated successfully on the first try, 32 required
two tries, 16 needed three tries and 37 needed four. Only
9 out of 37 passed on the fourth try leaving 28 bad points.
Only 159 of the points required corrections of three pixels
or more. The larger corrections indicate instances where
the correlation process was "lost" and had to "search" for
correlation rather than simply refine the predicted point.

Since 97.4 percent of the points in the standard case
passed on the first try, one of the "other" tests involved
the case where only one iteration was allowed in order to
judge the significance of the extra iterations. With only
one iteration, 250 points (vs. 28 previously) were judged to
be bad. This translates to a success rate of 92.3 percent
compared to 99.1 percent previously. The 92.3 percent rate
is quite high, but it is misleading in this case because the
operator had to interrupt the automatic process 15 times in
order to put the dot back "on the ground." This kept the

success rate high.

To demonstrate the success of the match-point adjustment option, the one-iteration test was run a second time but, when bad points were encountered, the match-point coordinates were replaced with values interpolated between good points on either side of the bad ones. These adjusted values were used in subsequent lines to predict the "next" match points and to compute window shaping parameters. The results of this test were that 65 points were found to be bad compared to 250 when interpolation was not used. Also, while the automatic process stopped 15 times before, now it did not stop at all. With the match-point adjustment option the results obtained with one iteration were almost as good as those obtained in the standard case.

DISCUSSION

General.
In the process of building up the Digital Interactive Mapping Program, various options were tried, tested and evaluated. Some were discarded and some were retained but it was found time and again that some combinations of options worked as well as others. The point is that there are several ways in which a suitable algorithm can be implemented and the DIMP is just one of several. The DIMP serves the purpose for which it was developed and it is an excellent tool for conducting tests for the purpose of algorithm development, simulation of other compilation schemes, and trade-off analyses. The main attribute of the DIMP is that it is interactive; and therefore, the operator can anticipate when and where interaction is necessary and prevent the propagation of errors. This is made possible because the DIMP provides a global view of the stereoscopic model and of the correlation data in the form of 3-D profile lines. Another important feature is that the operator can choose small discrete areas for compilation and test the effects of specific terrain features on the correlation process. This was important in the early stages of the DIMP development when appropriate logic had to be designed to handle the unique correlation problems imposed by features such as orchards. Test data derived from orchard areas eventually lead to a logic scheme that worked well in both the orchard and in general areas as well.

As far as the algorithm is concerned, two features can be signaled out as having major significance. First, the iterative capability was found to be a powerful means for maintaining good correlation results in adverse correlation areas. This technique essentially changes the DIMP philosophy, when required, from one of refinement to a predicted match point to one of a limited search operation over a small area. It was found generally that 90 percent of the time a refinement was sufficient but that the search operation kept the process on track in the poor areas thereby allowing the refinement process to remain appropriate in the good areas. In other words, without the search logic, the process would get lost in the bad areas, continue lost in the good areas and thereby negate the use of a refinement technique. A second major feature of the DIMP

algorithm is the option to replace the match-point coordinates of bad points with those derived by linear interpolation between good points. This is done at the completion of a row of correlations and therefore the advantages are available immediately to correct bad data in that row and enhance the chances for suitable correlations in the next row via more accurate match point prediction and window shaping.

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